Novel control system of the high-voltage IGBT-switch

A V Ponomarev[1,3], Y I Mamontov[2], A I Gusev[1] and M S Pedos[1]

[1] Institute of Electrophysics, 106 Amundsena Street, Ekaterinburg, 620016, Russia
[2] Ural Federal University, 19 Mira Street, Ekaterinburg, 620002, Russia
[3] Author to whom any correspondence should be addressed

E-Mail: apon@iep.uran.ru

Abstract. HV solid-state switch control circuit was developed and tested. The switch was made with series connection IGBT-transistors. The distinctive feature of the circuit is an ability to fine-tune the switching time of every transistor. Simultaneous switching provides balancing of the dynamic voltage at all switch elements. A separate control board switches on and off every transistor. On and off signals from the main conductor are sent to the board by current pulses of different polarity. A positive pulse provides the transistor switch-on, while a negative pulse provides their switch-off. The time interval between pulses defines the time when the switch is turned on. The minimum time when the switch is turned on equals to a few microseconds, while the maximum time is not limited. This paper shows the test results of 4 kV switch prototype. The switch was used to produce rectangular pulses of a microsecond range under resistive load. The possibility to generate the damped harmonic oscillations was also tested. On the basis of this approach, positive testing results open up a possibility to design switches under an operating voltage of tens kilovolts.

1. Introduction

Nowadays, the power semiconductor switching units are widely used in a Pulsed Power technology. The high-power switching requires a high-current equipment with a high working-voltage. However, the development of a single solid-state high-voltage device has physical limitations. A common method to produce a high-voltage solid-state switch uses a series connection of single devices on a stack [1]. Full control switch can be developed using MOSFETs or IGBTs. Today, such transistors are delivered by a number of companies. “Behlke” (www.behlke.com) offers the most extensive range of MOSFET and IGBT-based high-voltage switches. Unfortunately, a high cost and a limited variety of models promote the development and manufacturing of similar devices.

One of the most important aspects of the series operation of devices is to equalize the static and dynamic balancing of the voltage. The static voltage balancing can be simply achieved by connecting small balancing resistors in parallel with each device. The dynamic voltage balancing during the switching transient is much more difficult to achieve. Two dynamic voltage balancing techniques are available: the load-side balancing and the gate-side balancing. The load-side balancing employs a snubber circuit and/or a clamp circuit. The snubber circuit and/or clamp circuit provide the dynamic voltage balancing by limiting the device voltage rising rate and/or clamping the peak voltage. This

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technique, however, cannot be used for high-power applications since much loss is involved in the snubber and clamp circuits, which is proportional to the switching frequency. To solve this problem, an active gate control technique has been presented in the last few years, which does not degrade the switching transient characteristic. Each gate drive circuit should be actively controlled, so that all device voltages increased or decreased at the same rate [2].

This paper introduces a new method of designing a control circuit using the IGBT-based high-voltage switch with an active gate control technique.

2. Methods of designing control circuits using high-voltage switch units

There are several standard methods to control high-voltage switches by transistors. The most common control method uses an insulating transformer [3]. A series of isolated windings allows us synchronously to apply and remove a control voltage from switch transistors. Despite a seeming simplicity of the transformer control circuit, it has a number of disadvantages. The major drawback is its limited duration of a control pulse. This stems from the finite voltage-time integral of a control transformer core. Thus, a control circuit pulse width cannot exceed several to tens of microseconds. Moreover, the control circuit transformer design should be closely observed to reduce its leakage inductance. This will enable to reduce a control signals edge time. Another disadvantage of the control circuit transformer is a control signal's edge dependence on the number of controlled transistors and their gates capacity. Thus, the charging and discharging time of transistor gates will be proportional to the root of L and C product, where L stands for the secondary transformer circuit inductance and C stands for the total capacity of transistor gates.

Along with the transformer control circuits, there are opto-isolator circuits [4]. In this case, every transistor is controlled by a separate driver. The driver is triggered by a single fiber optic cable. This method is significantly more complicated than the previous one. To function, every isolated driver must be provided with a power supply for the circuit. To implement a parallel connection of light with the same intensity for each control fiber optic cable is a challenging task. Besides, the large dimensions of the device are caused by the numerous fiber optic control cables. The advantage of this circuit is that it allows us to deliver the control signals of any duration. In addition the length of transistors control signals edges does not depend on their number and their gates' capacity.

This paper proposes an original circuit design that encompasses all the benefits of the two methods mentioned above. To control the transistors, it uses a separate driver board with an isolated power supply. The control signals are supplied by a single wire loop (current loop) with the current pulses of different polarities. A positive current pulse determines the turn-on time of a transistors' switch signal. The negative current pulse turns off the transistors. Thus, the minimum pulse generation time equals to several microseconds, while the on-state switch duration time is not limited. Rogowski coils are installed on the driver boards and serve as current transducers. The advantage of these coils is their ability to differentiate the current input waveforms. As a result, Rogowski coil transmits a short-edge trigger signal to the driver's circuit. Shortening the edge of the control signal allows us to increase a precision of the transistors' switching time.

3. High-voltage switch control circuit using current loop

A simplified control circuit of the high-voltage switch using IGBTs is shown on Figure 1. A bipolar current control signal is generated by a bridge converter using VT1-VT4 transistors. The signal is generated in the form of pulses only at the moment of switching of the converter's transistors. The length of this pulse edge is determined by the C1 capacity and the inductance of the current loop, which, in its turn, is measured by the sum of the current loop inductance and the inductance of primary windings of T1-Tn Rogowski coils. Rogowski coils are made without any magnetic cores and have a low value of the magnetic coupling between windings. Thus, the inductance of the T1-Tn primary windings slightly exceeds the inductance of a usual wire. It can be concluded that the current loop inductance is determined only by its geometry. Considering the circuit characteristics, the half-period length of a current pulse was about 500 ns. When the signal was differentiated by Rogowski coils, the length of the signal's front edge from its secondary windings was shortened to a value of about 70 ns.

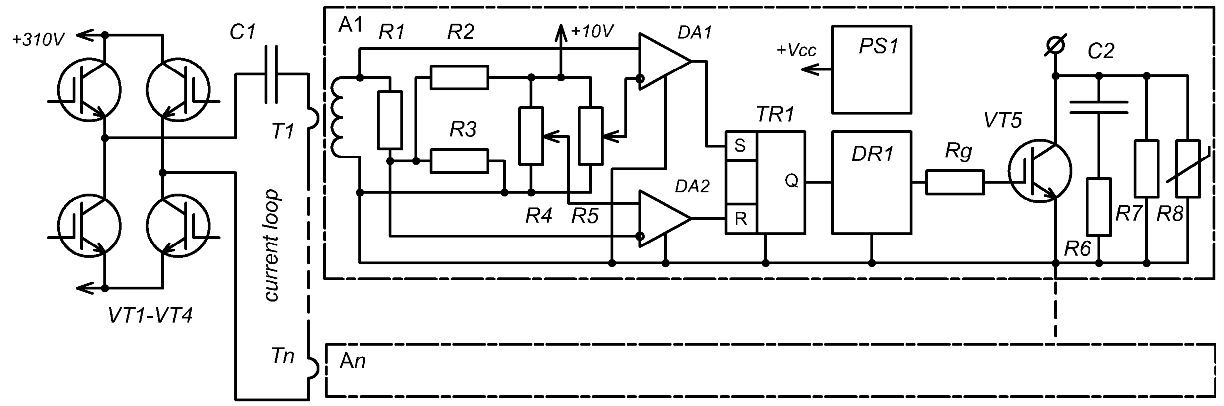

Figure 1. Control unit – circuit diagram.

The signals from Rogowski coils were sent out to the input of DA1 and DA2 high-speed comparators. While a positive signal switched on the DA1 comparator, the negative one switched on the DA2 comparator. The signals were sent out from the comparator outputs to TR1 RS-trigger, making it to toggle. The signals from the trigger were sent out to the DR1 driver. DR1 driver, in its turn, controlled the IGBT of VT5 switch.

The novelty and merit of the offered circuit configuration is the use of DR1 and DR2 comparators in the circuit. The comparators allow us to set independently the on/off time of every transistor switch with high precision. R4 and R5 trimmer potentiometers are used to change a reference voltage for the comparator response. The comparator checks this voltage with the input signal from the Rogowski coil (Figure 2b).

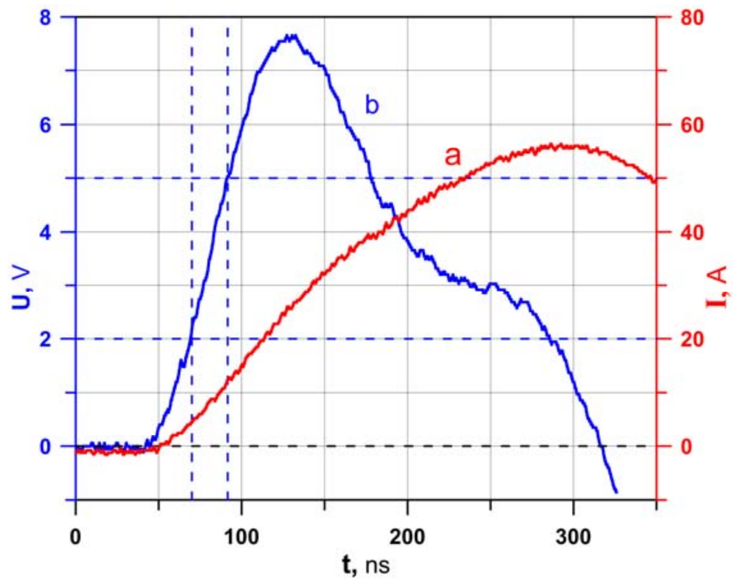

Figure 2. Control signals: a – current loop signal; b – output signal from the Rogowski coil.

Changing of the reference voltage changes the comparators switch on time. Figure 2 shows that when the comparator reference voltage to 3V (from 2 V to 5 V) changes, the response time will change to about 20 ns. Thus, changing the reference voltage, it becomes possible to change the on/off time of the transistor switch. The stabilized PS1 power supply allows us to change the reference voltage accurate to tenths and hundredths mV. This change of the reference voltage allows us to set

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the circuit response time accurate to split nanoseconds. The precise setting of the response time of every transistor provides a dynamic voltage balancing of its elements.

4. Experimental setup and methods

The efficiency and the operational capacity of the offered high-voltage switch control circuit method was tested and underwent an experimental verification. The switch prototype with a working-voltage of 4 kV was assembled for these experiments. The switch was made on two high-speed power IGBT-modules X2G75FD12P1 by Hivron. Each module included two series connected transistors with a maximum voltage of 1200 V and an average current of 75 A. The turn on and off of the transistors was carried out by four identical control plates.

The electric measurement facilities included a P6015A high-voltage probe and current shunts. The shunts had a proper signal rise time not exceeding 1 ns. A TDS 684B oscilloscope with 1 GHz bandwidth and Barth Electronics wide band signal attenuators were used for recording the output pulses.

5. Experimental results

The developed switch was tested in 2 modes. The first mode demonstrated the switch ability to generate the rectangular pulses of a microseconds range on a resistive load. The parallel-connected TVO resistors with a low inductance and a total resistance of 48 Ohms served as a load. Figure 3a shows the current and voltage signals on the load during rectangular pulse generation with the length of about 7 μs. Figure 3b and 3c shows the voltage and current curves at the time of the device switching on and off.

The second mode demonstrated the switch ability to generate the pulses of a damping harmonic oscillation. The received oscillation frequency slightly exceeded 1 MHz. In this test, the switch was installed into the gap of oscillating LC-circuit. Figure 3d shows the circuit current without an outfeed of the energy. The damping decrement, in this case, was determined by the losses in semiconductor elements and the resistive losses in conductors and instrument shunt. Considering a relatively low working-voltage of the switch, the maximum amplitude of the current did not exceed 20 A.

6. Discussion and conclusion

This paper introduces a high voltage solid state switch control circuit. On its basis, a switch prototype using 4 IGBTs at an applied voltage of up to 4 kV was designed. The switch underwent the tests, during which its characteristics were studied. Based on the conducted research, the following conclusions were made:

- A full control high voltage solid-state switch is able to generate the pulses of the length from several microseconds to the unlimited maximum length. These characteristics were obtained due to an offered control circuit method, using a current loop.
- The inductance of the controlling current loop has an insignificant effect on the values of generating pulses. Thus, its geometric dimensions are not limited, which, in its turn, will allow us to design the switches with a large number of steps and a high working-voltage.
- The tests of the designed switch revealed that on its basis, it is possible to build the square-wave generators, as well as the damped harmonic oscillation pulse generators.
- It has been observed that there is no overvoltage on the switch at its turn-off. It is probably connected to the existence of tail currents that are typical for the IGBTs. The accumulated charges in the collector of a transistor do not allow us to break the running current abruptly, preventing, in this way, the voltage spike on the stray circuit inductances.

The device demonstrated a high reliability. To set up the switching turn-on and turn-off times of every transistor is simple and takes up a minimum time. Another advantage of the device is its reduced size compared to the circuits using a fiber-optics technology.

The disadvantage of the device is a lack of the feedback in the control circuit reported in [5]. As a result, an electrical circuit drift and a dynamic voltage imbalance on the switch elements can occur.

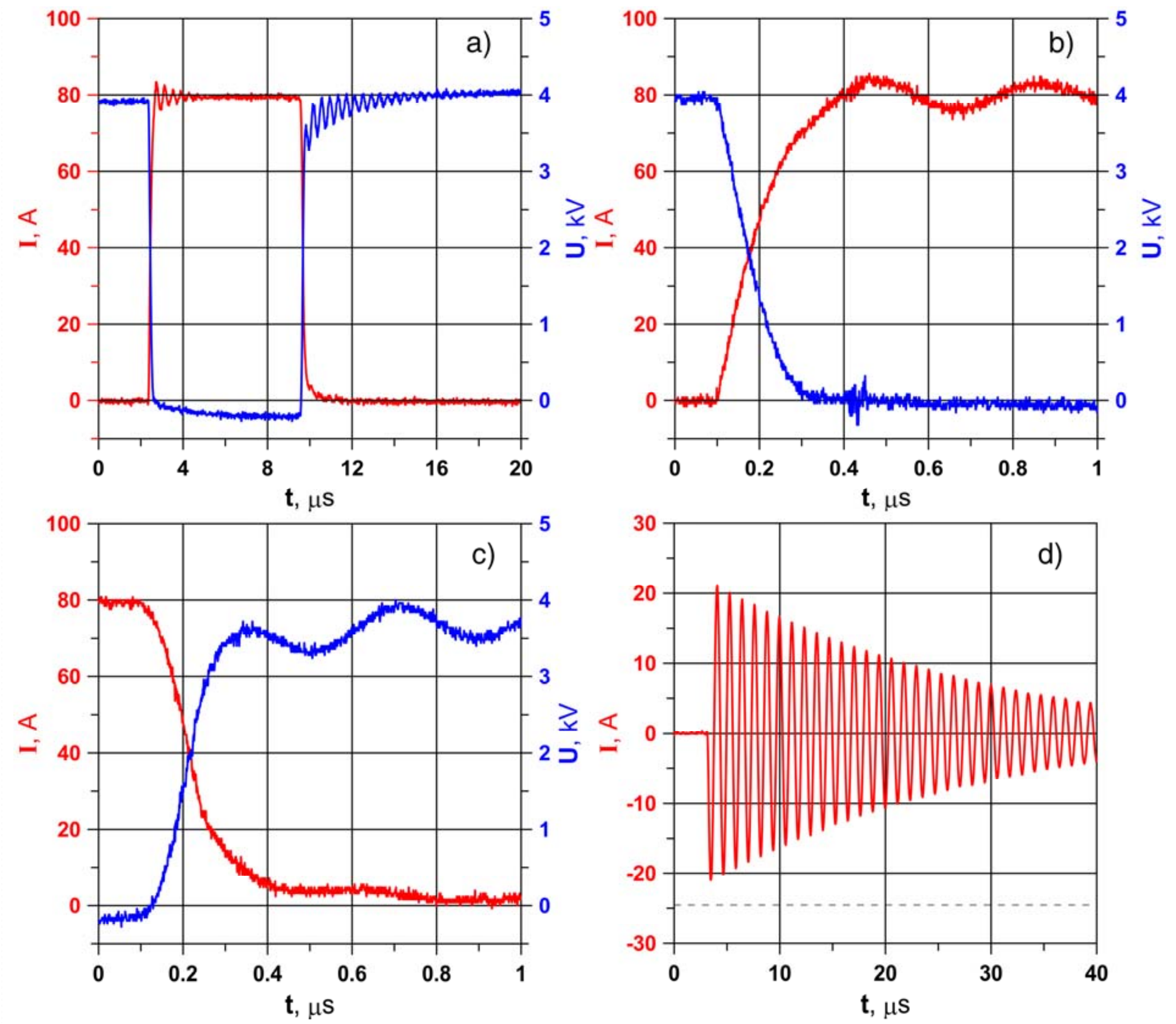

Figure 3. Voltage and current curves of switch operation in two modes: a-c – the formation of a rectangular pulse; d – the formation of damped harmonic oscillations.

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